Is inflatino production duirng preheating a threat to nucleosynthesis?

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We discuss the production of inflatino the superpartner of the inflaton due to vacuum fluctuations during preheating and argue that they do decay alongwith the inflaton to produce a thermal bath. Therefore they do not survive until nucleosynthsis to pose a threat to it.

PRESENTED AT

COSMO-01
Rovaniemi, Finland,
August 29 – September 4, 2001

[1]presented the talk, based on the work in Ref. [13].

1 Introduction

Inflation is perhaps one of the best paradigms of the early Universe which solves some of the problems of the standard Big Bang cosmology [1]. In addition, quantum fluctuations of the inflaton field generated during inflation keep their imprint intact to match the observed anisotropy in the present Universe which is one part in 10^5 [2]. Once inflation ends, the homogeneous inflaton field oscillates coherently around the bottom of the potential. The inflaton oscillations decay when the Hubble parameter $H \sim \Gamma_\phi$, where Γ_ϕ is the decay rate. The decay rate essentially depends on the inflaton couplings to other particles [3]. Recently it has been realized that there can be an explosive particle production due to non-perturbative effects [4]. Effectively, the problem turns out to be quantizing the bosonic and the fermionic fields in a time-varying inflaton background. The production of bosons and fermions differs in its nature due to Pauli's exclusion principle, which prohibits excessive production of fermions compared to their bosonic counterparts [5].

The spin $3/2$ gravitino occurs in supersymmetric theories as a superpartner of the graviton [6]. A massless gravitino only possesses $\pm 3/2$ helicity states. However, once supersymmetry is broken the gravitinos become massive, and they possess all four helicity states. Soon after realizing that the helicity $\pm 3/2$ states of a massive gravitino can be produced non-perturbatively [7], it was found out that the helicity $\pm 1/2$ states can also be produced from vacuum fluctuations [8, 9, 10]. They are produced even more abundantly compared to helicity $\pm 3/2$ states due to the Goldstino nature of helicity $\pm 1/2$ states which implies the absence of any Planck mass suppression in their couplings.

If supersymmetry is required to solve the gauge hierarchy problem, then, in the gravity mediated supersymmetry breaking, the gravitino gets a mass around, $\mathcal{O}(\text{TeV})$. The lifetime of the gravitino is quite long, $\tau_{3/2} \sim \text{M}_\text{p}^2/m_{3/2}^3 \sim 10^5 (m_{3/2}/TeV)^{-3}$sec, and hence its decay products can affect light element abundances from big bang nucleosynthesis [11]. This leads to a strong constraint on the reheat temperature, $T_{\text{rh}} \leq 10^{10}$ GeV, in order not to overproduce gravitinos in the thermal bath [12]. It also tightly constrains any non-perturbative gravitino production during preheating.

Here we briefly discuss the decay of inflatinos and helicity $\pm 1/2$ gravitinos produced during preheating (details can be found in Ref. [13]). We begin with an introduction of a supersymmetric inflationary model with a single multiplet, and then discuss decay rates of the inflaton and its superpartner inflatino in two models: with Planck mass suppressed coupling, and with Yukawa couplings to the visible sector. We then establish an equivalence between the helicity $\pm 1/2$ gravitino coupling to the supercurrent and that of the inflatino in the supergravity Lagrangian when the amplitude of the inflaton oscillations are small compared to the Planck mass. In the last section we give a qualitative discussion upon the gravitino decay when more than one chiral fields are present.

2 Inflaton decaying via gravitational coupling

As a first example we consider a new inflation model proposed in Ref. [14] where the inflaton sector and the visible sector interact only gravitationally. While setting the cosmological constant at the global minimum to zero, the simplest form of a superpotential emerges [14]

$$\mathrm{I} = \frac{\Delta^2}{\mathrm{M}}(\Phi - \mathrm{M})^2\,, \tag{1}$$

where Δ determines the scale of inflation, Φ is the inflaton superfield, and $\mathrm{M} \equiv \mathrm{M_P}/\sqrt{8\pi}$ is the reduced Planck mass. The amplitude of the density perturbations produced during inflation is fixed by COBE, leading to $\Delta/\mathrm{M} \approx 5\times 10^{-3}$. The scalar potential derived from the above superpotential has a form

$$V = e^{\sum_j (|\Phi_j|/\mathrm{M})^2}\left(\sum_k \left|\frac{\partial W_{\rm tot}}{\partial \phi_k} + \frac{\phi_k^* W_{\rm tot}}{\mathrm{M}^2}\right|^2 \right. \\ \left. -3\frac{|W_{\rm tot}|^2}{\mathrm{M}^2}\right)\,, \tag{2}$$

where we have assumed minimal Kähler function and we consider the total superpotential to be

$$W_{\rm tot} = \mathrm{I} + \mathrm{L}\,, \tag{3}$$

where L represents the visible sector. The leading order term in the scalar potential generates trilinear coupling to the scalars in the visible sector with a gravitational strength $\sim \Delta^2/\mathrm{M}^2$, corresponding to a decay rate $\Gamma_\phi \sim (\Delta^6/\mathrm{M}^5)$ for the inflaton [14]. Then the reheat temperature of the Universe can be estimated by

$$T_{\rm rh} \sim \left(\frac{30}{\pi^2 g_*}\right)^{1/4} (\Gamma_\phi \mathrm{M})^{1/2} \approx 10^{-1}\frac{\Delta^3}{\mathrm{M}^2}\,. \tag{4}$$

For $\Delta/\mathrm{M} \sim 5\times 10^{-3}$, the reheat temperature is around $T_{\rm r} \sim 10^{10}$ GeV.

The equation of motion for the helicity $\pm 1/2$ gravitino in a cosmological background has been derived in the literature by using alternative approaches [8, 9, 10]. The important realization is that when the amplitude of the oscillations is much smaller than the reduced Planck mass, the equation of motion for the helicity $\pm 1/2$ gravitino is effectively that of the goldstino (which is the inflatino up to a phase) in a global supersymmetric limit [8, 9, 10]. The evolution of the inflatino, which we define here as $\tilde{\phi}$, follows [9]

$$i\gamma^0 \dot{\tilde{\phi}} - \hat{k}\tilde{\phi} - m_{\rm eff}\tilde{\phi} = 0\,, \tag{5}$$

where $\hat{k} = \gamma^i k_i$, and k_i are components of the physical momentum, while γ^i are the gamma matrices.

When the amplitude of the inflaton oscillations $|\phi| \ll \mathrm{M}$, the effective mass of the helicity $\pm 1/2$ gravitinos, for a single chiral superfield and after a phase rotation, is simply the mass of the fermionic component of the inflaton field [9]. This is the same as the mass of the inflaton which is Δ^2/M for the superpotential in Eq.(3). On the other hand, the helicity $\pm 3/2$ gravitinos have a mass given by [6]

$$m_{\pm 3/2} \equiv e^{\phi^2/2\mathrm{M}^2} \frac{|\mathrm{I}|}{\mathrm{M}^2} \sim \frac{\Delta^2}{\mathrm{M}} \left(\frac{\phi(t)}{\mathrm{M}} \right)^2 . \tag{6}$$

This leads to a simple inequality in various mass scales

$$m_\phi \approx m_{\pm 1/2} > H > m_{\pm 3/2} . \tag{7}$$

Now we analyze the decay rate of the inflatino. Consider the following interaction found in the Lagrangian [6]

$$|\det\, e|^{-1} \mathcal{L} = -\frac{1}{2} e^{G/2} G^i G^j \bar{\chi}_i \chi_{j\mathrm{L}} + \mathrm{h.c.}\,, \tag{8}$$

where G^i is the derivative of the Kähler potential with respect to left and right chiral components. We can fix the index; $i = \phi$, corresponding to the inflaton sector. This leaves the other index j to run on the chiral components of the visible sector L. It turns out that the inflatino $\tilde{\phi}$ decays into scalars φ and fermions χ in the visible sector through terms like $\Delta^2/\mathrm{M}^2 \tilde{\phi} \chi \phi$. This yields

$$\Gamma_{\tilde{\phi}} \approx \frac{\Delta^6}{\mathrm{M}^5} . \tag{9}$$

This decay rate, not surprisingly, is the same as the decay rate of the inflaton. Now, if we argue that the helicity $\pm 1/2$ states of the gravitino essentially behave as inflatino when the amplitude of the inflaton oscillations $|\phi| \ll \mathrm{M}$, then , we may argue that the helicity $\pm 1/2$ gravitinos decay alongwith the inflaton. Intuitively, this makes sense, because if supersymmetry is restored at the bottom of the potential in the absolute minimum, then only the $\pm 3/2$ components of the gravitino should survive. However, to be more concrete we must study the gravitino interactions.

The gravitino interaction terms appear from the couplings between the gravitino field and the supercurrent

$$\mathcal{L}_{\psi J} = \frac{1}{\sqrt{2}\mathrm{M}} \bar{\Psi}_\mu \not{D} \varphi^{*j} \gamma^\mu \chi_{j\mathrm{L}} + \frac{i}{\sqrt{2}\mathrm{M}} e^{G/2} G^i \bar{\Psi}_\mu \gamma^\mu \chi_{i\mathrm{L}} + \mathrm{h.c.}\,, \tag{10}$$

where μ stands for the space-time index, χ_i is a fermionic field and φ^i is its bosonic superpartner. Here the subscripts i, j correspond to the visible sector L, which contains the light degrees of freedom. We have neglected the vector multiplets in the above equation and assumed ϕ to be homogeneous. The total derivative $D_\mu$is defined by

$$D_\mu = \partial_\mu + \frac{1}{2}\omega_{\mu ab}\sigma^{ab}\,, \tag{11}$$

where $\omega_{\mu ab}$ is the spin connection.

The interaction terms proportional to $\gamma^\mu\Psi_\mu$ are usually not necessary in a static limit of the background field (i.e. inflaton field), because $\gamma^\mu\Psi_\mu = 0$ acts as a constraint for a gravitino field in a static background. However, this need not be true in a non-static background. It has been shown that in an expanding Universe, and in a time-varying inflaton background, $\pm 1/2$ helicity states follow $\gamma_\mu\Psi^\mu \neq 0$ [8]. Although, the same constraint continues to hold good for the helicity $\pm 3/2$ components of the gravitino in the same background along with the Dirac equation [7].

After several oscillations of the inflaton field $|\phi| \ll \mathrm{M}$, or, equivalently $H \ll m$. All the fields whose effective mass is larger than the Hubble parameter during the oscillations of the inflaton would actually not feel any effect of curvature of the Universe. Therefore we replace $\pm 1/2$ helicity of the gravitino by an ansatz

$$\Psi_\mu \sim \sqrt{\frac{2}{3}}\frac{\mathrm{M}}{\rho_\phi^{1/2}}\partial_\mu\eta\,, \tag{12}$$

where η represents the goldstino. At this moment this prescription seems to be unwarranted, but, we shall see that this choice of derivative wavefunction leads to the interactions of the helicity $\pm 1/2$ gravitino to that of the inflatino. A similar expression has beenpreviously used in Refs. [15], where the authors have been studying the scattering processes of the helicity $\pm 1/2$ gravitino in a limiting case when the energy scale of the gravitino is larger than its mass in a flat space-time. Here, again we have a similar situation where the helicity $\pm 1/2$ gravitino does not feel the Hubble expansion, however, the only difference is that now supersymmetry is broken due to the oscillating scalar field rather than the static vacuum contribution. This is the reason why instead of the gravitino mass $m_{3/2} \sim 1$ TeV, we now have $\rho_\phi^{1/2}/\mathrm{M}$.

Substituting Eq. (12), in Eq. (10) and after some algebraic manipulations, for details see [13], we derive an effective Lagrangian

$$\mathcal{L}_{\mathrm{eff}} \approx e^{G/2}\frac{\partial G}{\partial \phi}\frac{\partial G}{\partial \varphi}\bar{\tilde{\phi}}\chi_{\mathrm{L}} + \mathrm{h.c.}\,, \tag{13}$$

which is the inflatino coupling in Eq. (8) to the leading order. This is the most important equivalence which establishes the fact that, since, for any successful inflationary model inflaton has to decay, and, so does the inflatino, the helicity $\pm 1/2$ component of the gravitino must also decay if the inflaton oscillations is the only viable source of supersymmetry breaking at that time. Our result is strictly correct for a single chiral field responsible for supersymmetry breaking.

3 Model with a Yukawa coupling to the inflaton

As a second example we consider a model with a following superpotential

$$W = \frac{1}{2}m\Phi^2 + \frac{1}{2}h\Phi\Sigma^2\,, \tag{14}$$

where Φ contains the inflaton field, which is responsible for the slow-roll inflation. However, now the inflaton field has an explicit Yukawa coupling to the matter sector given by the second term in Eq. (14). Such a superpotential leads to interaction terms $hm\phi\sigma\sigma$, $h\phi\tilde{\sigma}\tilde{\sigma}$, $h\tilde{\phi}\tilde{\sigma}\sigma$, where ϕ is the inflaton field, $\tilde{\phi}$ is the inflatino, σ is a light bosonic field, and its fermionic partner has been denoted by $\tilde{\sigma}$. The estimated rate of the inflaton decaying to fermionic component $\tilde{\sigma}\ \tilde{\sigma}$ is given by $\Gamma_\phi \sim (h^2/8\pi)m$.

In general the Yukawa coupling between Φ and Σ multiplets can also result in the oscillations along the σ field. This may lead to a more complicated situation where supersymmtery is broken by several multiplets. However, it is possible to prevent this provided we require that the ϕ-induced mass to the σ field is much smaller than the Hubble expansion, i.e. $h\phi < H$, which implies $h < m/\mathrm{M}$. We note that this will also insure that σ and $\tilde{\sigma}$ are not produced via parametric resonance. A viable choice of parameters which can lead to an inflationary paradigm is; $m = 10^{13}$ GeV, and, a small Yukawa coupling $h = 10^{-7}$, which ensures that at late stages of the inflaton oscillations, $\phi/\mathrm{M} \leq 10^{-14}$, the inflaton is decaying perturbatively.

We may now repeat the same analysis as in the previous case which eventually leads to (for details see [13])

$$\mathcal{L}_{\rm eff} \sim h\sigma^*\bar{\tilde{\phi}}\tilde{\sigma}_{\rm R} + {\rm h.c.}\,. \tag{15}$$

This reinsures our earlier claim that the equivalence between the helicity $\pm 1/2$ gravitino and the goldstino is viable at late times of the inflaton oscillations. This equivalence is not only important for studying the production of the helicity $\pm 1/2$ components of the gravitino, but also describing the decay of the helicity $\pm 1/2$ gravitino.

4 Models with several multiplets

Once we invoke more than one sectors, and treat them at equal level, the problem of gravitino production becomes more complicated. This problem has been addressed in

Refs. [9, 10] to some extent. In this case it has been realized that the goldstino is a linear combination of all the fermions, and as a result, even if we use the goldstino-gravitino equivalence we cannot in general guarantee that a major contribution to the goldstino mass is coming from the fermionic component of the inflaton. Interesting question would be to address a problem where there exists a hidden sector which is responsible for supersymmetry breaking in that sector, and also responsible for mediating supersymmetry breaking gravitationally to the observable sector. In such a case the gravitino will have an effective mass $\sim \mathcal{O}(\text{TeV})$ at present vacuum. So, keeping this in mind we may consider a simple toy model with a following superpotential

$$W = \frac{1}{2}m_1\Phi^2 + m_2^2[Z + (2-\sqrt{3})\mathrm{M}]\,, \tag{16}$$

where Φ and Z are inflaton and Polonyi multiplets respectively. We assume that ϕ field is responsible for inflation, so we set $m_1 = 10^{13}$ GeV to produce adequate density perturbation, while setting $m_2 = 10^{11}$ GeV for giving an effective mass to the gravitino around $\mathcal{O}(\text{TeV})$. An interesting discussion regarding this model has been sketched in Ref. [10].

Now one derives a set of coupled equations for the helicity $\pm 1/2$ gravitino and other fermionic degrees of freedom [9, 10]. It has been shown in Ref. [10], that in a global supersymmetric limit, this set of equations is reduced to a coupled set of equations for the goldstino and the transverse combination of the fermions. For the above superpotential Eq. (16), the inflaton and the Polonyi sectors have only gravitational interactions. The fermionic components $\tilde{\phi}$ and $\tilde{z}$ have masses m_1 and zero respectively in the global supersymmetric limit. The goldstino in this model is a linear combination of the fermionic components from both the sectors. As long as supersymmtery breaking is dominated by the inflaton field, the helicity $\pm 1/2$ gravitinos essentially behave as inflatino. Then the helicity $\pm 1/2$ gravitinos produced during preheating will essentially decay because they are essentially the inflatino components and so their couplings are determined in the same fashion as that of the inflaton.

However, the energy density in the inflaton sector is decreasing in time, and, when the Hubble expansion $\sim H < \mathcal{O}(\text{TeV})$, the $\tilde{z}$ component dominates the goldstino. Usually, the mixing between the inflatino and $\tilde{z}$ is minimal and Planck mass suppressed, so, the fermions which are produced during preheating will decay again in the form of inflatino and cause no trouble for nucleosynthsis. Once z field starts oscillating at $H \approx \mathcal{O}(\text{TeV})$, supersymmetry is broken by the oscillations in z direction also, and, as a result gravitinos can as well be excited. One may suspect that the late production of the helicity $\pm 1/2$ gravitinos will dominate and the problem of gravitino decay still persists. The suspicion is not fully correct because the number density of the helicities $\pm 1/2$ and $\pm 3/2$ are more or less equal now. This is because the only time-varying scale is due to time-varying mass of the gravitino $\sim e^{zz^*/2\mathrm{M}^2}|W|/\mathrm{M}^2$. The presence of the Planck mass suppression prohibits explosive production of the gravitinos at late times. But, now the problem could be much more severe, because these gravitinos with both the helicities are produced much later, and their effective masses are also very small roughly of the order of TeV. This leads to extremely slow decay rate of these gravitinos which may cause a problem to the Big Bang nucleosynthesis. Furthermore, the oscillating Polonyi field leads to an even more serious problem, i.e. the moduli problem, of which there is no satisfactory way out.

Finally, if the fermionic components mix freely, the inflatinos can be converted to $\tilde{z}$ (which is the field eventually eaten by the gravitino). This presumably occurs around the time when contributions to supersymmtery breaking from the inflation sector and the Polonyi sector become comparable. This problem is analogue to the neutrino flavor conversion and the relevant question is to ask the conversion probability. As mentioned, we beileve that an effcicient conversion will not take place for the Polonyi model. An efficient conversion nevertheless results in a large abundance of $\tilde{z}$ fermion, on top of what is produced due to oscillations of the Polonyi field. We notice that if the inflatino decays before $H \approx \mathcal{O}(\text{TeV})$, then the abundance of the inflatinos prior to conversion will decrease leading to a smaller abundance for $\tilde{z}$ (and consequently helicity $\pm 1/2$ gravitinos) even after an efficient conversion.

5 Conclusion

Our main result is that in models with one multiplet the coupling of helicity $\pm 1/2$ gravitinos to the supercurrent leads to the same interactions as that of the inflatinos when the amplitude of the inflaton oscillations is small $|\phi| \ll \text{M}$. Then we have argued that the production of helicity $\pm 1/2$ states of the gravitino cannot be considered as a threat for nucleosynthesis. The helicity $\pm 1/2$ states remember their goldstino nature and this is the reason why they are produced very efficiently compared to the helicity $\pm 3/2$ states. However, the same goldstino nature also reults in the decay of the helicity $\pm 1/2$ gravitino alongwith the inflaton. The requirement that the inflaton must decay to give a successful nucleosynthesis, leads to an efficient decay of the goldstino, or, the helicity $\pm 1/2$ gravitinos. This argument holds perfectly well for a single chiral superfield where the goldstino is inflatino with some additional phase. This argument can also be applied to models where there are more than one sectors of supersymetry breaking, provided supersymmetry breaking, provided that the inflationary scale is much higher than the scale of superymmtery breaking in the hidden sector. Such a situation can arise if there exists a Polonyi field in the hidden sector, which we have briefly discussed. However, we still lack a complete formal tools to explore all possibilities such as mixing between the fermionic components of the inflaton sector and the Polonyi sector. This can in principle change the abundance of the helicity $\pm 1/2$ component of the gravitinos and a detailed study is certainly required in this direction.

The above discussion does not apply to the helicity $\pm 3/2$ gravitinos. The production of these states during preheating is always Planck mass suppressed and so is their couplings to the matter, hence they decay quite late and can be dangerous for nucleosynthsis [7].

ACKNOWLEDGEMENTS

The work of R.A. was supported by "Sonderforchschungsbereich 375 für Astro-Teilchenphysik" der Deutschen Forschungsgemeinschaft.

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